

# Spontaneous Combustion of Char Stockpiles

Esmail R. Monazam

*Department of Mechanical and Aerospace Engineering, West Virginia University,  
Morgantown, West Virginia 26505*

Lawrence J. Shadle\* and Abolghasem Shamsi

*U.S. Department of Energy, Federal Energy Technology Center, P.O. Box 880,  
Morgantown, West Virginia 26507-0880*

A transient one-dimensional spontaneous heating model has been formulated to describe the spontaneous heating process at relatively low temperatures. The model consists of three differential equations describing the temperature, oxygen, and moisture concentration in a char pile. These equations have been solved numerically by a finite difference technique, and the influence of the initial char temperature, char reactivity, particle size, and moisture content on the process of spontaneous heating have been examined. Sensitivities are presented for the most important factors affecting the self-heating of coal, including a comparison of coal pile characteristics with and without moisture adsorption, desorption, and migration. This model was also validated against data from large-scale spontaneous heating tests.

## Introduction

High-moisture low-rank coals have been found to be expensive and difficult to transport and result in a low heat output upon combustion. Drying and partial pyrolysis of coals minimize these problems but raise another by increasing the susceptibility of the dried coal to autoignition.

When dried coal or char is stored in the presence of air, spontaneous heating poses a serious problem for both producers and users. The phenomena of spontaneous heating may be caused by a low-temperature oxidation,<sup>1,2</sup> possibly induced by the heat of wetting.<sup>3</sup> Low-temperature oxidation is an exothermic reaction, and its rate increases with the temperature.<sup>4</sup> If the heat generated is more than the amount of heat dissipated by conduction and convection, heat is accumulated and the temperature increases.<sup>5</sup> When the temperature reaches the ignition temperature, the coal or char autoignites.

The tendency toward spontaneous combustion also increases considerably through drying.<sup>6,7</sup> Drying to low moisture levels removes inherent moisture from the coal structure in addition to surface moisture. This greatly increases the surface area available for oxidation.

This study investigates the behavior of char piles over a wide range of conditions to understand the physical phenomena that influence spontaneous ignition. Of particular interest is the influence of moisture on the spontaneous heating process.

There are only a few models in which the influence of moisture on the process is incorporated.<sup>8–10</sup> However, most investigators have concluded that the moisture content is one of the most important factors affecting the self-heating of coal. However, no one has yet described what role moisture adsorption, desorption, and migration play in coal stockpile stability. These phenomena are investigated in this study.

## Experimental Section

**Previous Model.** The phenomenon of spontaneous heating is complex and can only be treated by means of a mathematical model. The first model of spontaneous heating was developed by Van Doornum,<sup>11</sup> based on assumptions that heat transfer occurs only by conduction, a constant oxygen concentration in the stockpile, and neglecting moisture adsorption or desorption. Van Doornum grouped the characteristics of the coal and external factors into dimensionless parameters that completely determine the thermal behavior of the coal. Sondreal and Ellman<sup>6</sup> developed a more elaborate model that also allowed calculation of the temperature profile. The most recent and comprehensive models are those of Brooks and Glasser,<sup>12</sup> Schmal et al.,<sup>8</sup> Arisoy and Akgün,<sup>10</sup> and Krishnaswamy et

(1) Jones, J. C.; Vais M. *J. Hazard. Mater.* **1991**, *26*, 203–212.

(2) Carras, J. N.; Young, B. C. *Prog. Energy Combust. Sci.* **1994**, *20*, 1–15.

(3) Walker, I. K. *Fire Res. Abstr. Rev.* **1967**, *9*, 5–22.

(4) Kajji, R.; Hishinuma, Y.; Nakamura, Y. *Fuel* **1985**, *64*, 297–302.

(5) Ünal, S. *Fuel Sci. Technol. Int.* **1995**, *13* (9), 1103–1120.

(6) Sondreal, E. A.; Ellman R. C. *U.S. Bur. Mines Rep. Invest.* **1974**, *7887*.

(7) Li, Y. H.; Skinner, J. L. Deactivation of Dried Subbituminous Coal. Presented at 1985 AIChE Spring Meeting, Houston, Texas, March 24–28.

(8) Schmal, D.; Duyzer, J. H.; Van Heuven, J. W. *Fuel* **1985**, *64*, 963–972.

(9) Nordon, P. *Fuel* **1979**, *58*, 450–456.

(10) Arisoy, A.; Akgün, F. *Fuel* **1994**, *73*, 281–286.

(11) Van Doornum, G. A. W. *J. Inst. Fuel* **1954**, *27*, 482.

(12) Brooks, K.; Glasser D. *Fuel* **1986**, *65*, 1035–1041.

al.<sup>13</sup> Brooks and Glasser<sup>12</sup> developed a one-dimensional model that considered the combination of conductive and convective heat transfer within the pile and concluded that particle size and voidage play a crucial role in determining the safety of a coal dump. The most complete model is that of Schmal et al.,<sup>8</sup> which considered the transport of heat by conduction, convection, and evaporation/condensation of coal moisture. The model assumed that the gas velocity in the pile was independent of time and space. Schmal et al. concluded that the most important parameters in spontaneous heating are the initial temperature, evaporation, and condensation of coal moisture and the degree of compaction in the pile.<sup>8</sup>

**Model Formulation.** To describe the behavior of spontaneous heating in a stockpile, a three-dimensional model is needed. However, to simplify the analysis and to obtain simple criteria predicting the key factors that affect self-heating, a one-dimensional model (length and width  $\gg$  height) that only accounts for vertical variation is considered. In this study, the following assumptions are made in formulating the model: (1) The model is one-dimensional, nonsteady state. (2) Char consumption is neglected. Oxidation at close to ambient temperature does not consume appreciable amounts of char. Therefore, actual burning of char is not modeled. (3) Only natural convection of Darcy's law is applied. Since velocities within the pile are very low, Darcy's law is accurate. (4) The local temperatures of the char and gas phase are assumed to be equal. This assumption is supported by the mathematical simulations conducted by Edwards.<sup>14</sup> (5) The dependence of the oxidation rate on the temperature is described by means of the Arrhenius equation. (6) Accumulation of heat in the gas phase is neglected. (7) The char pile is homogeneous and isotropic, with uniform spherical particles. (8) The mathematical model was developed in the form of a set of differential equations which are described in following section.

The equation of energy conservation states is

$$(1 - \epsilon)\rho_c c_{pc} \frac{\partial T}{\partial t} = K_{eff} \frac{\partial^2 T}{\partial Y^2} - \rho_g C_{pg} V_g \frac{\partial T}{\partial Y} + (1 - \epsilon)\dot{r}_{O_2} \Delta H_{O_2} \pm (1 - \epsilon)\dot{r}_{H_2O} \Delta H_{H_2O} \quad (1)$$

The reaction of char with oxygen and water vapor generates energy that, in a practical situation, divides into two portions: one portion is dissipated because of conduction and convection and the other portion is converted into internal energy, which manifests itself as a rise in temperature.<sup>15</sup> To relate the rise in temperature to the increase of internal energy, one must know the specific heat,  $C_{pc}$ , of the char as a function of both the moisture content and temperature. Therefore, the specific heats of as-received char are obtained from the following relationship<sup>16</sup>

$$C_{pc} = \sum_{i=1}^3 w_i C_{pi} \quad (1.1)$$

where  $C_{p1}$ ,  $C_{p2}$ , and  $C_{p3}$  are specific heats of the as-received, dried ash-free (daf) char, ash, and moisture respectively, and  $w_1$ ,  $w_2$ , and  $w_3$  are the mass fractions in the as-received char of the daf char, ash, and moisture, respectively.

The effective thermal conductivity,  $K_{eff}$ , is one of the main factors that affects the rate of heat dissipation. Heat is carried away from the hot spots of the pile by conduction through the char-air-moisture mass. The effective thermal conductivity of the pile is determined by the thermal conductivities of the individual constituents and is obtained by

$$K_{eff} = w_3 K_{H_2O} + \frac{(1 - w_3)}{\frac{\epsilon'}{K_{gas}} + \frac{(1 - \epsilon')}{K_{char}}} \quad (1.2)$$

where  $\epsilon'$  is the effective voidage and is obtained from Russell's<sup>16</sup> general correlation as

$$\epsilon' = 1 - (1 - \epsilon)^{1/3} \quad (1.3)$$

The char thermal conductivity,  $K_{char}$ , is obtained from the experimental data of Badzioch et al.<sup>17</sup> as

$$K_{char} = (0.876 \times 10^{-3}) + (0.805 \times 10^{-6} T) - (0.642 \times 10^{-8} T^2) + (0.716 \times 10^{-11} T^3) \quad (1.4)$$

where  $T$  is the char temperature (K).

A factor was used to account for convective heat dissipation from hot spots caused by air circulation. The velocity of air circulating,  $V_g$ , may be calculated by applying the Darcy law and Boussinesq assumption<sup>18</sup>

$$V_g = \frac{\kappa g \rho_g}{\mu} \left(1 - \frac{T_0}{T}\right) \quad (1.5)$$

where  $\kappa$  is the permeability and is determined from the following expression:<sup>19</sup>

$$\kappa = \frac{d_p^2 \epsilon^3}{150(1 - \epsilon)^2} \quad (1.6)$$

The major heat generation mechanism responsible for the self-heating of the char stockpile is the oxidation of char by oxygen from the air and the possible catalytic effects of other compounds (e.g., water<sup>3</sup>). The rate of low-temperature oxidation of coal/char,  $\dot{r}_{O_2}$ , depends on at least five factors:<sup>9</sup> the partial pressure of oxygen, the carbon structure, the moisture content, the temperature, and the amount of previous oxidation. It is for this reason that a number of different models have been developed describing the coal/char oxidation process.<sup>20-22</sup> In this study, the oxygen consumption rate was adopted after Krishnaswamy et al.<sup>22</sup> for Black Thunder coal and is expressed as

$$\dot{r}_{O_2} = \eta_G (1 - \epsilon) K_1 C_{O_2} \quad (1.7)$$

where

$$K_1 = (8.828 \times 10^6) \exp(-6950/T) \quad (1.8)$$

The global effectiveness factor,  $\eta_G$ , is defined such that the rate of oxygen consumption can be related to the oxygen concentration in the bulk gas phase. Its value depends on the particle size, mass transfer coefficient, diffusivity of oxygen, and rate constant. The global effectiveness factor approaches unity for relatively dry coal/char ( $\sim 10\%$  moisture content),  $0.1 < d_p(\text{cm}) < 1$ , and  $300 \text{ K} < T < 400 \text{ K}$ .<sup>22</sup> The heat of oxidation reaction,  $\Delta H_{O_2}$ , following Krishnaswamy et al.<sup>13</sup> is taken as 94.0 kcal/gmol.

Moisture plays an important role in the behavior of stockpiles of coal/char.<sup>2</sup> The coal/char moisture content for a given

(13) Krishnaswamy, S.; Agarwal, P. K.; Gunn, R. D. *Fuel* **1996**, 75, 353-362.

(14) Edwards, J. C. *Metall. Soc. AIME* **1983**, A83-21.

(15) Nordon, P.; Bainbridge, N. W. *Fuel* **1979**, 58, 450-456.

(16) Merrick, D. *Fuel* **1983**, 62, 540-546.

(17) Badzioch, S.; Gregory, D. R.; Field, M. A. *Fuel* **1964**, 43, 267-280.

(18) Anderson, P.; Glasser, D. *Int. J. Heat Mass Transfer* **1990**, 33(6), 1321-1330.

(19) Brooks, K.; Balakotaiah, V.; Luss, D. *AIChE J.* **1988**, 34(3), 353-365.

(20) Kam, A. Y.; Hixson, A. N.; Perlmutter, D. D. *Chem. Eng. Sci.* **1976**, 31, 815-819.

(21) Karsner, G. G.; Perlmutter, D. D. *Fuel* **1982**, 61, 29-34.

(22) Krishnaswamy, S.; Gunn, R. D.; Agarwal, P. K. *Fuel* **1996**, 75, 344-352.

value of relative humidity is described by its adsorption/desorption isotherm.<sup>23</sup> When an increase in the humidity causes an uptake of moisture in coal, heat is generated. This heat is in addition to that heat generated from oxidation. On the other hand, when there is a decrease in the humidity of the surroundings relative to the vapor pressure exerted by the coal moisture, water is desorbed from the coal. This evaporation consumes the heat produced by the oxidation and results in a lower coal temperature.<sup>5</sup> Thus, the effects of coal moisture and the surrounding humidity cannot be divorced from one another.

In this study, it was assumed that the sorption of both adsorbed and free water occur simultaneously.<sup>23</sup> The rate of water sorption and desorption was modeled as a shrinking core such that the rate is related to the vapor density gradient between the saturated liquid at the vaporization/condensation surface,  $r_v$ , and the gas phase. The approach is based on that of Monazam et al.<sup>23</sup> Therefore, using the spherical geometry assumption, the rate of water sorption is written as

$$r_{H_2O} = \frac{3r_v^2}{R_0^3} M_e \rho_c \frac{dr_v}{dt} \quad (1.9)$$

The rate of movement of the sorption surface is obtained as<sup>23</sup>

$$\frac{dr_v}{dt} = \frac{R_0^2 K_g (\rho_v^g - \rho_v^{r_v})}{M_e \rho_c r_v^2 \left( 1 + BI_m \left( \frac{R_0}{r_v} - 1 \right) \right)} \quad (1.10)$$

where  $BI_m$  and  $K_g$  are the mass transfer Biot number ( $K_g R_0 / D_{H_2O}$ ) and the mass transfer coefficient (cm/s). The vapor density,  $\rho_v^{r_v}$ , is obtained as

$$\rho_v^{r_v} = \phi \rho_g^{r_v} \quad (1.11)$$

The relationship between the coal/char equilibrium moisture content, temperature, and relative humidity is obtained using Henderson's equation<sup>24</sup> as

$$1 - \phi = \exp(-KTM_e^n) \quad (1.12)$$

where  $\phi$  is the relative humidity and the factor  $K$  and exponent  $n$  vary for different materials.

The moisture in the coal particle is calculated by

$$\rho_c \frac{\partial M}{\partial t} = r_{H_2O} \quad (1.13)$$

where  $M$  is the coal moisture content (kg/kg).

The latent heat of vaporization,  $\Delta H_{H_2O}$ , is calculated precisely using the Clapeyron equation. The equation is written as follows

$$\Delta H_{H_2O} = T(V_v - V_l) \frac{dP_v}{dT} \quad (1.14)$$

In eq 1.14, the vapor pressure of the moisture in the coal/char,  $P_v$ , is determined from the following equation

$$P_v = \phi P_g \quad (1.15)$$

$dP_v/dT$  in eq 1.14 is obtained by differentiating  $P_v$  in eq 1.15 with respect to  $T$  or

$$\frac{dP_v}{dT} = P_g \frac{d\phi}{dT} + \phi \frac{dP_g}{dT} \quad (1.16)$$

The saturation vapor pressure of water,  $P_g$ , is calculated by the empirical equation of Keenan and Keyes.<sup>25</sup>  $d\phi/dT$  in eq 1.16 is obtained by differentiating  $\phi$  in eq 1.12 with respect to  $T$  or

$$\frac{d\phi}{dT} = KM_e^n (1 - \phi) \quad (1.17)$$

The equation of oxygen mass conservation states is

$$\epsilon \frac{\partial C_{O_2}}{\partial t} = \epsilon D_{O_2} \frac{\partial^2 C_{O_2}}{\partial Y^2} - V_g \frac{\partial C_{O_2}}{\partial Y} - (1 - \epsilon) r_{O_2} \quad (2)$$

The equation of moisture mass conservation states is

$$\epsilon \frac{\partial C_{H_2O}}{\partial t} = \epsilon D_{H_2O} \frac{\partial^2 C_{H_2O}}{\partial Y^2} - V_g \frac{\partial C_{H_2O}}{\partial Y} \pm (1 - \epsilon) r_{H_2O} \quad (3)$$

with the boundary conditions at the surface of the pile,  $Y = 0$

$$T = T_{air}, C_{O_2} = 0.21 C_{air}, C_{H_2O} = C_{H_2O_{air}} \quad (4)$$

and at the bottom of the pile (ground interface),  $Y = L$

$$\frac{\partial T}{\partial Y} = 0, \frac{\partial C_{O_2}}{\partial Y} = 0, \frac{\partial C_{H_2O}}{\partial Y} = 0 \quad (5)$$

The initial condition is at  $t = 0$

$$T = T_0, C_{O_2} = 0.21 C_{air}, C_{H_2O} = C_{H_2O_{air}} \quad (6)$$

Equations 1–6 were transformed into the appropriate difference form for solution using an implicit Crank–Nicholson scheme; the result was solved numerically using Thomas' algorithm method.

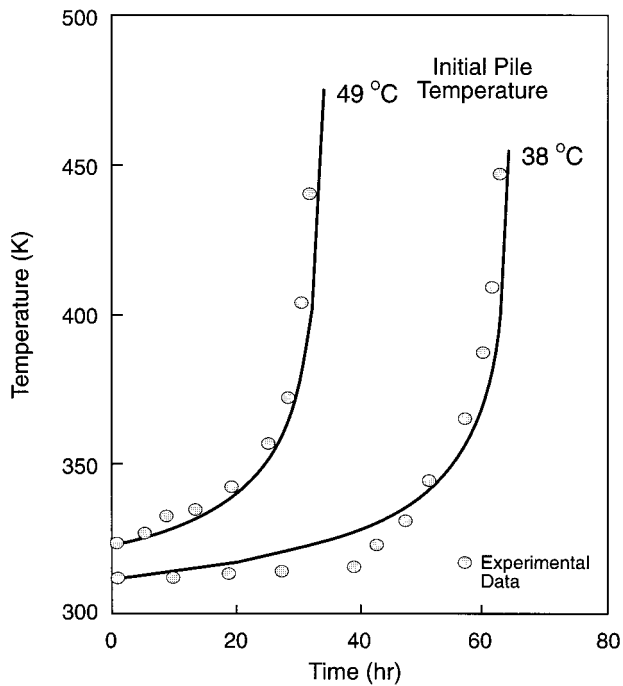
## Results and Discussion

To demonstrate the various effects that may occur during self-heating, it is convenient to first examine the behavior before mass transfer of moisture is taken into account. Equations 1–6 were solved with the rate of moisture adsorption/desorption,  $r_{H_2O}$ , set equal to zero (*model A*). Model A was then validated against experimental data obtained by Li and Skinner<sup>7</sup> from large-scale spontaneous heating tests using pilot-plant dried coal. The spontaneous heating apparatus was a large cylinder 61 cm in diameter by 244 cm in length. Temperatures were measured at about 30-cm intervals over the length of the vessel. Each test consumed about 365 kg of coal. Black Thunder coal dried to 10% moisture was subjected to 2.832e4 scc/min flow of dry air. The authors did not report the relative humidity of the air. A comparison between the model predictions and the experimental data is displayed in Figure 1. Good agreement was obtained for each sample studied. As proven by experimental testing, the model predicted that if a dried coal pile was exposed to air of 25 °C, with initial temperatures of 38 and 49 °C, a local hot spot (temperature above 200 °C) developed after 60 and 30 h, respectively. The temperature profiles within the pile obtained by the model are illustrated in Figure 2 for

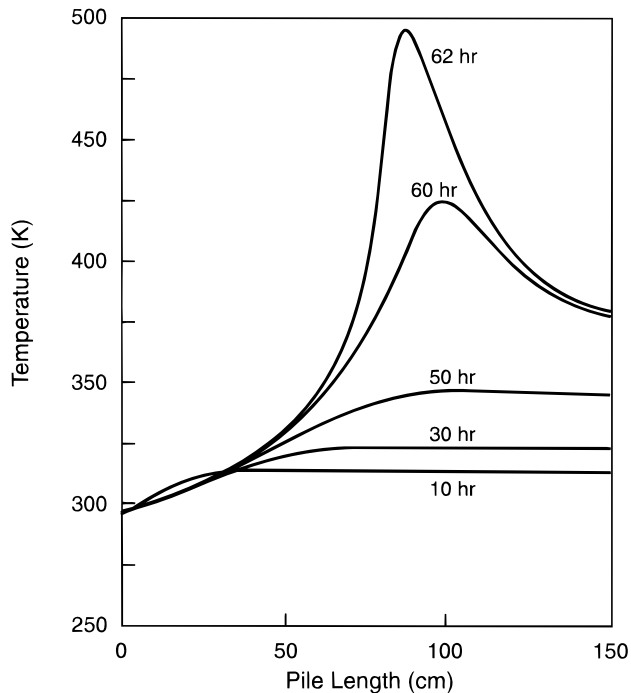
(23) Monazam, E. R.; Shadle, L. J.; Evans, R.; Schroeder, K. *Energy Fuels* **1998**, *12*, 1299.

(24) Henderson, S. M. *Agric. Eng.* **1952**, *1*, 29–32.

(25) Keenan, J. H.; Keyes, F. G. *Thermodynamic Properties of Steam*; Wiley: New York, 1936.



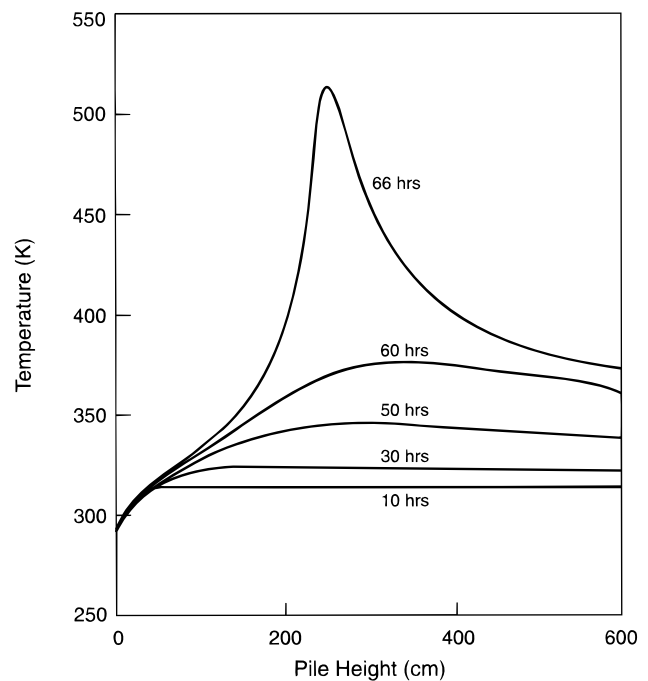
**Figure 1.** Comparison of the predicted maximum temperature (—) and experimental data<sup>7</sup> (●) for two different initial temperatures using model A.



**Figure 2.** Temperature profiles through the coal pile at different times using model A.

the dried coal pile with an initial temperature of 38 °C. The temperature rose with time, and eventually a hot spot appeared at about 100 cm from the air inlet.

After initial testing of the model, eqs 1–6 were solved, incorporating the rate of moisture adsorption /desorption,  $h_{H_2O}$  (model B). Simulation of temperature, oxygen, and moisture profiles through the pile after different periods of time are presented in Figures 3–5, respectively. It is clear that the spontaneous heating process was extremely fast under the baseline conditions of a particle size of 6 mm, a temperature of 38 °C, a void



**Figure 3.** Temperature profiles through the coal pile at different times (base conditions) using model B.

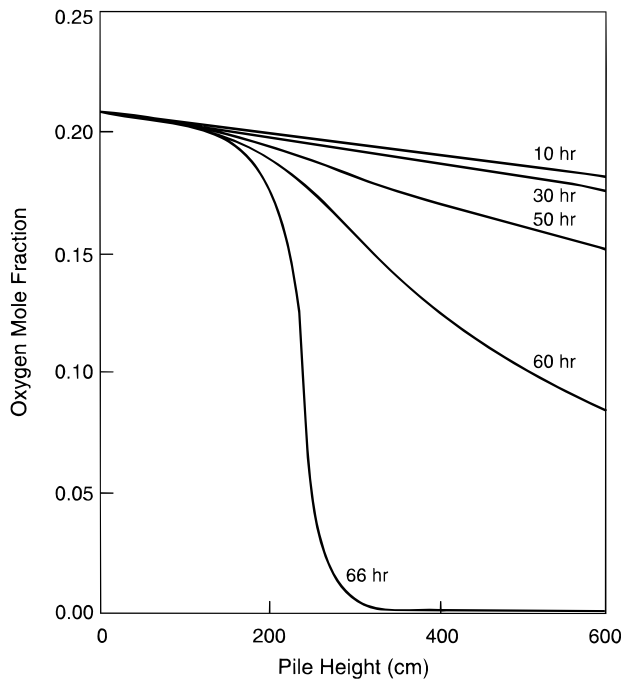
fraction of 0.4, a moisture content of 8%, a pile length of 600 cm, and preexponential factor for those of Black Thunder coal.<sup>21</sup>

For the baseline conditions, the maximum temperature appeared at ~255 cm (Figure 3) from the top surface after 50 h. Above this level, the temperature dropped because the rate of heat lost due to the conduction was greater than the rate of heat generation due to the oxidation. Below this level, the temperature dropped because of an oxygen shortage. As the temperature started to rise, the oxygen concentration rapidly decreased and achieved a minimum in the region of maximum temperature (Figure 4). The shortage of oxygen in the downstream region of the pile is illustrated in Figure 4. The change in char moisture content because of evaporation and condensation is presented in Figure 5. The moisture evaporated in the region of maximum temperature and condensed in the downstream region, leading to a local increase in moisture content.

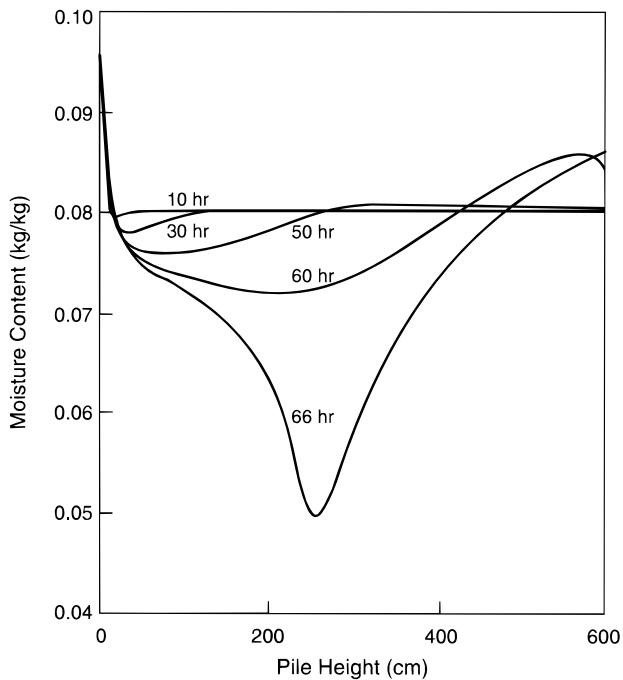
A comparison of maximum temperature profiles for models A ( $h_{H_2O} = 0$ ) and B ( $h_{H_2O} \neq 0$ ) as a function of time is illustrated in Figure 6 for the base conditions. Figure 6 clearly shows that the rate of hydration has no initial effect. However, as time proceeds and the temperature of the pile is increased above 50 °C, a difference between models A and B developed. Also, the rate of hydration had a strong influence on the location of ignition, as demonstrated in Figure 7. Model A predicted the ignition location at ~130 cm; model B predicted it to be at ~260 cm.

The models were compared at various combinations of moisture content, initial pile temperature, particle size, voidage, and coal reactivity (16 cases). For all cases studied, model B exhibited longer ignition delay times and deeper high-temperature location than model A. Similar findings were reported by Schmal et al.<sup>8</sup> This is because of the drying of the coal (Figure 5), which





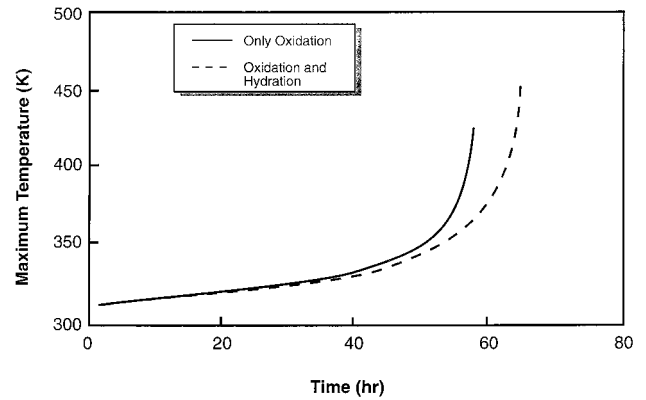
**Figure 4.** Oxygen profile through the coal pile at different times (base conditions) using model B.



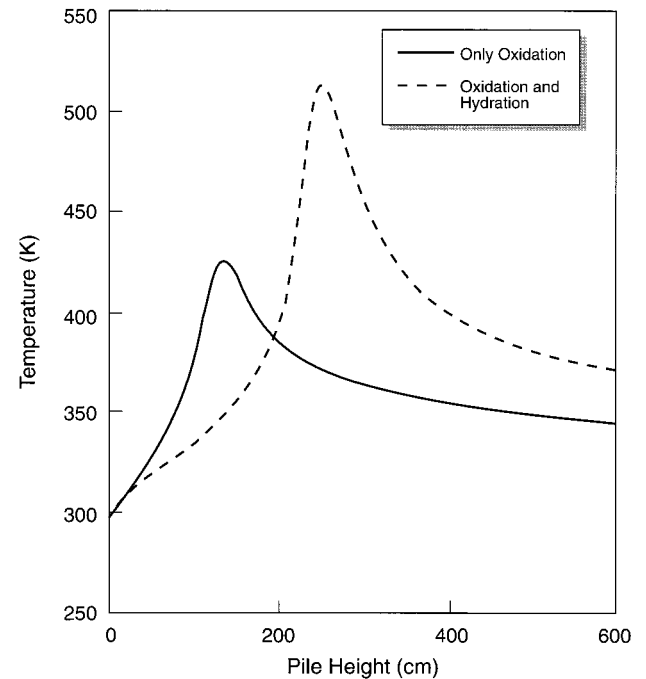
**Figure 5.** Char moisture content profile through the coal pile at different times (base conditions) using model B.

decreased the rate of the temperature rise for model B. This demonstrates that even hydration models fail to predict the observed effect that moisture enhances the tendency for self-heating. This analysis provides further strength to the arguments<sup>3</sup> that water plays additional roles to those considered here. The most promising roles of moisture not included in this model are (1) an oxidation catalyst, (2) an initiator or intermediate in the combustion mechanism, or (3) a swelling agent in opening the coal structure.

**Sensitivity Study.** To further test the utility of the model, the effects of some key physical parameters in



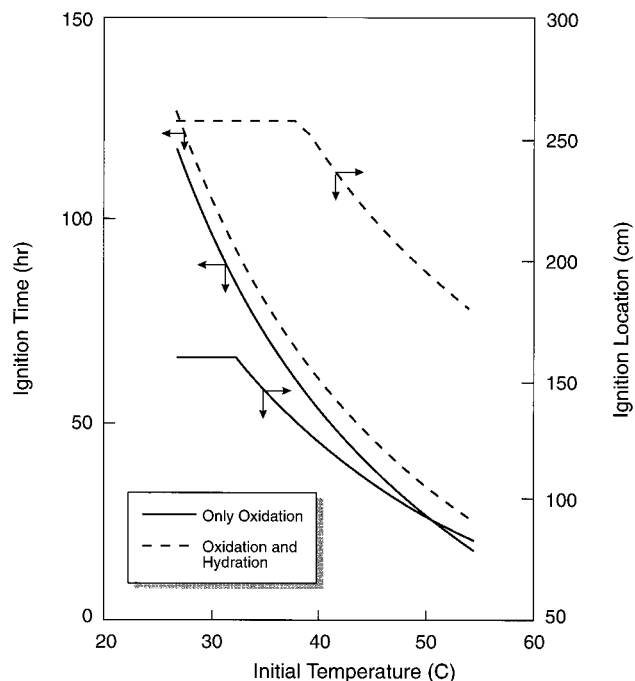
**Figure 6.** Influence of char moisture on maximum temperature (base conditions) comparing model A with model B.



**Figure 7.** Comparison of temperature profiles from model A with model B taken at the time of ignition.

the model on the pile ignition time and location were examined. Parameters tested included the initial pile temperature, preexponential factor in oxidation reaction, particle size, and moisture content. The ignition time and location were then examined for each of the model input parameters of interest by holding the other parameters constant while varying the value of the parameter under study.

**Influence of Initial Temperature.** The effect of the coal pile initial temperature on the resulting ignition time and location is illustrated in Figure 8. The ignition time ( $t_i$ ) and location ( $y_i$ ) are defined as when and where the thermal runaway occurs; an indication of this is the accelerated portion of the curve in Figure 3. These predictions demonstrated that the time for the coal pile to autoignite is a strong function of the initial temperature. This dependence is understandable because the rate of heat generation (i.e., coal oxidation) within the coal pile is exponentially dependent on the coal pile temperature. As the accumulation of heat in the coal pile increases, as reflected by the increase in temperature, the time for autoignition decreases.



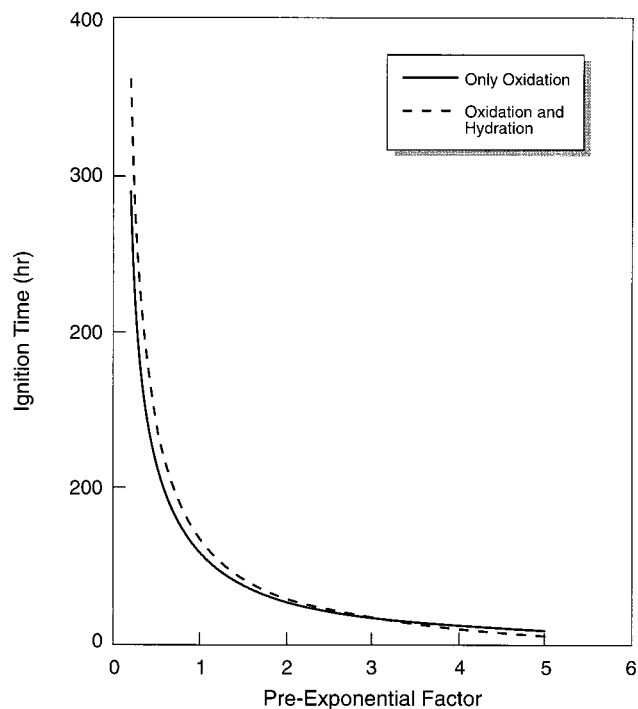
**Figure 8.** Influence of initial temperature on ignition time and location for model A and model B.

The initial temperature (up to  $\sim 33^\circ\text{C}$  for model A and  $\sim 40^\circ\text{C}$  for model B) had no effect on the ignition location (Figure 8). However, as the initial temperature increased beyond these levels, the ignition location was decreased from the surface. This is mainly because of the difference in the rate of heat generation and the heat lost. The rate of heat generation is much larger at higher initial temperatures than is the rate of heat lost because of conduction, convection, and evaporation.

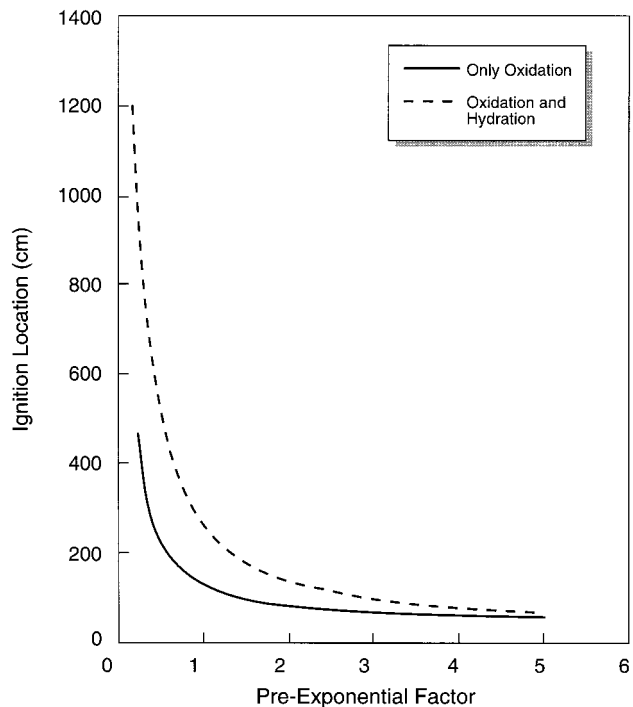
**Influence of the Preexponential Factor.** To examine the effect of different coals or char on spontaneous heating with different reactivities, the preexponential factor in the oxidation reaction was varied by 2 orders of magnitude. Such differences reflect changes in pore structures, the level of organic maturation, and the presence of catalytic materials. The effects of changing the preexponential factors on the resulting ignition time and location are illustrated in Figures 9 and 10. The prediction illustrated by Figure 9 clearly indicated that the larger this factor, the less safe is the coal pile. The observed functional dependence arose from the fact that the rate of oxygen consumption is proportional to the preexponential factor. Therefore, the more reactive the char, the greater the rate of oxygen depletion and the greater the tendency toward spontaneous heating.

By increasing the preexponential factor, the ignition's location decreases from the surface (Figure 10). These results reflect the fact that the rate of oxygen depletion is less for less-reactive coal/char, which thereby allows the oxygen to penetrate further into the coal pile, thus leading to a longer ignition time and a deeper ignition location. These results clearly indicated the strong sensitivity of the model on the oxidation rate.

**Influence of Particle Size.** The effects of variation in the particle size on ignition time and location is illustrated in Figure 11. These predictions indicated that the ignition time is not significantly affected by

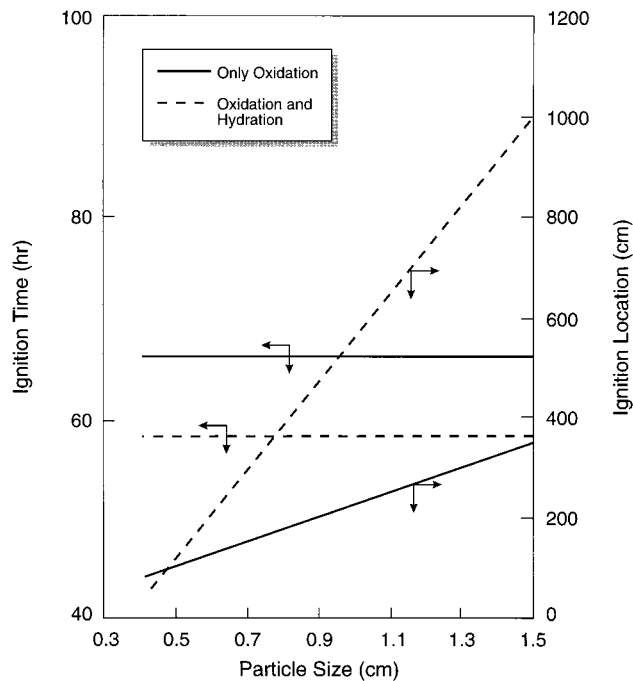


**Figure 9.** Influence of preexponential factor on ignition time for model A and model B.

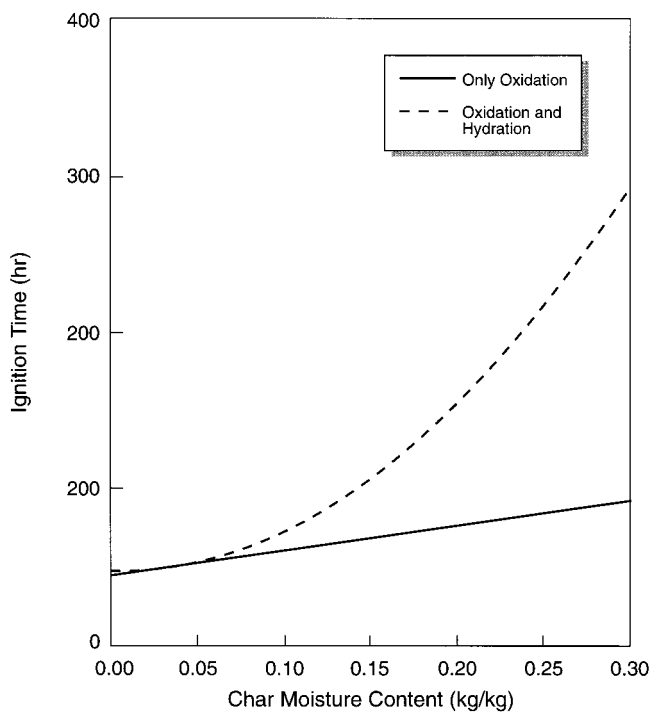


**Figure 10.** Influence of preexponential factor on ignition location for model A and model B.

changing the particle size from 0.2 to 1.5 cm. However, the variation in particle size had a strong impact on the location of ignition. These results are a direct consequences of eq 1, which indicates that the rate of oxygen reaction,  $r_{O_2}$ , is independent of particle size ( $0.1 < d_p < 1.5$ ). However, the convective heat transfer caused by the gas velocity,  $V_g$ , is proportional to the particle diameter. Therefore, the larger the char particle, the greater is the heat lost because of convection, thus leading to a deeper ignition location.

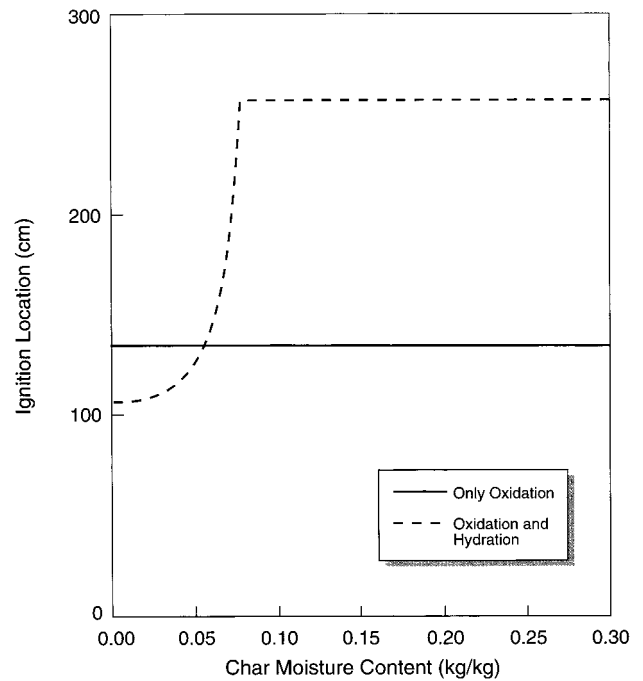


**Figure 11.** Influence of particle size on ignition time and location for model A and model B.



**Figure 12.** Influence of char moisture content on ignition time for model A and model B.

**Influence of Coal/Char Moisture Content.** The dependence of ignition time and location on moisture is illustrated in Figures 12 and 13, respectively. Increases in char pile moisture resulted in increased ignition times (Figure 12). The observed functional dependence arises from the fact that the rate of heat accumulation is proportional to the coal pile's thermal diffusivity ( $K_{eff}/\rho_c C_{pc}$ ), which in turn is inversely proportional to the coal pile's moisture content. The time required to reach autoignition is much longer for model B than for model A (Figure 12). This is mainly because of evaporation and condensation phenomena.



**Figure 13.** Influence of char moisture content on ignition location for model A and model B.

Figure 13 also illustrates that the ignition location is not affected by model A. However, the predictions from model B show that by decreasing the coal pile moisture below 8%, the height of ignition location also decreases. The height of ignition location is not affected for a coal pile moisture greater than 8%.

## Conclusion

A mathematical model for the spontaneous heating of char stockpiles has been developed. Excellent agreement between the model predictions and measurements of temperature and ignition time demonstrated that the model was accurate and reliable. In its present form, the model can be used to provide qualitative insight into the influence of the different parameters.

A sensitivity analysis was performed on the temperature and ignition time. The coal pile's initial temperature had a strong effect on the ignition time. The time needed for the temperature to reach  $\sim 400$  K was about 5 times shorter with an initial temperature of  $50^\circ\text{C}$  than at  $25^\circ\text{C}$ . The coal pile's moisture content also had a strong impact on the ignition time. A coal pile with a higher moisture content had a lower tendency toward autoignition. The particle size had an inverse relationship to spontaneous heating. A coal pile with the smaller particles had a greater risk of spontaneous heating.

**Acknowledgment.** The authors acknowledge the Department of Energy for funding the research through the Fossil Energy's Integrated Gasification Combined-Cycle program.

## Glossary

### Nomenclature

$C_{\text{air}}$	air concentration ( $\text{g cm}^{-3}$ )
$C_{\text{H}_2\text{O}}$	moisture concentration ( $\text{g cm}^{-3}$ )

$C_{O_2}$	oxygen concentration ( $\text{g cm}^{-3}$ )
$C_{pc}$	specific heat of char pile ( $\text{cal g}^{-1} \text{K}^{-1}$ )
$C_{pg}$	specific heat of gas ( $\text{cal g}^{-1} \text{K}^{-1}$ )
$D_{O_2}$	diffusivity of oxygen into the pile ( $\text{cm}^2 \text{s}^{-1}$ )
$D_{H_2O}$	diffusivity of water through the particle ( $\text{cm}^2 \text{s}^{-1}$ )
$g$	gravity ( $\text{cm s}^{-2}$ )
$K$	experimental constant
$K_1$	oxidation rate constant ( $\text{s}^{-1}$ )
$K_{\text{char}}$	char thermal conductivity ( $\text{cal s}^{-1} \text{cm}^{-1} \text{K}^{-1}$ )
$K_{\text{eff}}$	effective thermal conductivity ( $\text{cal s}^{-1} \text{cm}^{-1} \text{K}^{-1}$ )
$K_g$	mass transfer coefficient ( $\text{cm s}^{-1}$ )
$K_{\text{gas}}$	gas thermal conductivity ( $\text{cal s}^{-1} \text{cm}^{-1} \text{K}^{-1}$ )
$K_{H_2O}$	moisture thermal conductivity ( $\text{cal s}^{-1} \text{cm}^{-1} \text{K}^{-1}$ )
$L$	pile length (cm)
$M$	moisture content ( $\text{kg kg}^{-1}$ )
$M_e$	equilibrium moisture content ( $\text{kg kg}^{-1}$ )
$n$	experimental constant
$P_v$	vapor pressure
$P_g$	saturation pressure
$\dot{m}_{H_2O}$	rate of water adsorption/desorption ( $\text{g cm}^{-3} \text{s}^{-1}$ )
$\dot{m}_{O_2}$	oxidation rate ( $\text{g cm}^{-3} \text{s}^{-1}$ )
$r_v$	vapor radius (cm)

$R_0$	particle radius (cm)
$t$	time (s)
$T$	temperature (K)
$T_0$	surrounding temperature (K)
$V_g$	gas velocity ( $\text{cm s}^{-1}$ )
$V_l$	liquid volume ( $\text{cm}^3$ )
$V_v$	vapor volume ( $\text{cm}^3$ )
$w$	weight fraction
$Y$	distance in the Y-direction (cm)
$\Delta H_{H_2O}$	heat of vaporization ( $\text{cal g}^{-1}$ )
$\Delta H_{O_2}$	heat of reaction ( $\text{cal g}^{-1}$ )

#### *Greek Symbols*

$\epsilon$	pile voidage
$\eta_G$	global effectiveness factor
$\rho_c$	pile density ( $\text{g cm}^{-3}$ )
$\rho_g$	gas density ( $\text{g cm}^{-3}$ )
$\rho_g^{r_v}$	saturation density at the vapor radius ( $\text{g cm}^{-3}$ )
$\rho_v^{r_v}$	vapor density at the vapor radius ( $\text{g cm}^{-3}$ )
$\phi$	relative humidity